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Status of NASA's Stirling Space Power Converter Program

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STATUS OF NASA'S STIRLING SPACE POWER CONVERTER PROGRAM

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ABSTRACT

An overview is presented of the NASA Lewis Research Center Free-Piston Stirling Space Power Converter Technology Program. This work is being conducted under NASA's Civil Space Technology Initiative. The goal of the CSTI High Capacity Power Element is to develop the technology base needed to meet the long duration, high capacity power requirements for future NASA space initiatives. Efforts are focused upon increasing system power output and system thermal and electric energy conversion efficiency at least fivefold over current SP-100 technology, and on achieving systems that are compatible with space nuclear reactors.

This paper will discuss Stirling experience in space and progress toward 1050 K and 1300 K Stirling Space Power Converters. Fabrication is nearly completed for the 1050 K Component Test Power Converter (CTPC); results of motoring tests of the cold end (525 K), are presented. The success of these and future designs is dependent upon supporting research and technology efforts including heat pipes, bearings, superalloy joining technologies, high efficiency alternators, life and reliability testing and predictive methodologies. This paper provides an update of progress in some of these technologies leading off with a discussion of free-piston Stirling experience in space.

INTRODUCTION

The NASA Stirling Space Power Converter Program originated in 1983 as part of the SP-100 Program - a joint NASA, DOD, and DOE effort to develop the technology necessary to provide space nuclear power systems for military and civil applications. The SP-100 Program is directed toward the development and validation of technology for a versatile space nuclear reactor power system having the capability to generate from tens to hundreds of kilowatts of electrical power for at least seven years at full power. A 2.5 MWt reactor with thermoelectric power conversion is the baseline space nuclear power system, scheduled for development by the year 2001. The Stirling Space Power Program is a part of NASA's Civil Space Technology Initiative (CSTI) High Capacity Power Program, a program to complement and enhance SP-100, which is aimed at identifying and developing technology options for achieving significantly higher performance and system growth potential, significantly reduced specific mass, and longer lifetimes at acceptable reliability for civil applications.

The specific elements of the CSTI High Capacity Power Project include Conversion Systems (Stirling and Thermoelectric), Thermal Management, Power Management, System Diagnostics, and Environmental Interactions. Technology advancement in all of these areas, including materials, is required to assure the gains in power and performance illustrated in Figure 1. The SP-100

reactor, with thermoelectrics, is itself a significant advance in power density at 20 W/kg. NASA mission needs to date have been met with Photovoltaic/Energy Storage Systems; or Radioisotope Thermoelectric Generators (RTG), where PV systems would be too heavy or too bulky, or would not function because of distance from the Sun. Space Station Freedom, in low earth orbit is the largest power requirement foreseen by the year 2000 at 75 - 100 kWe. The Space Exploration Initiative, proposing to return to the Moon to stay and then to journey to Mars in the 21st century, necessitates the development of advanced power systems such as the 1050 K Stirling and the 1300 K Stirling highlighted in Figure 1.

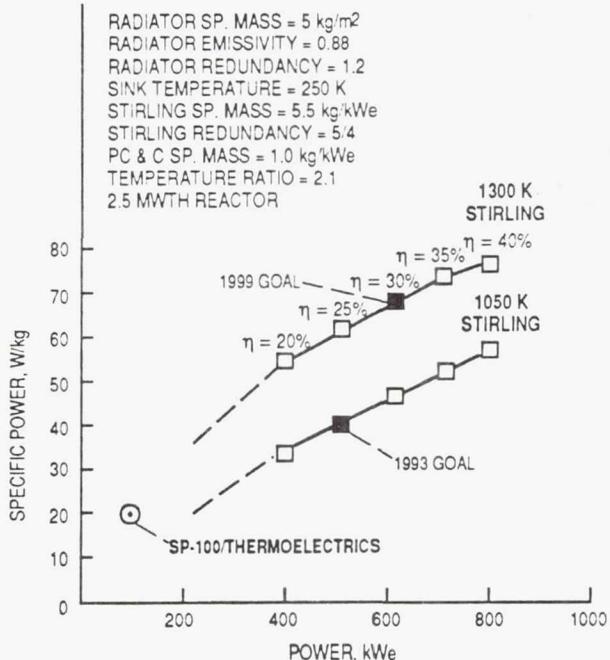


FIGURE 1 - EXTENDING SP-100 REACTOR POWER SYSTEMS CAPABILITY; THERMOELECTRICS (TE) AND STIRLING

The development of advanced Stirling Power conversion is based upon the high efficiency of dynamic power systems (Stirling has the highest potential) and the long-life potential of the free-piston, linear alternator concept first invented in the U.S. in 1963. Stirling efficiency enables a 550 kWe lunar base nuclear power system mass such that only two heavy lift launch vehicles are required to lift the mass (120 Metric Tons) to low earth orbit. By comparison, a solar PV system using current technology with battery energy storage would require 1300 heavy lift launch vehicles to deliver 550 kWe capability to low earth orbit.

STIRLING DEVELOPMENT

A conceptual design for a lunar base is shown in Figure 2. An 800 kWe nuclear Stirling system is shown in the foreground. The precursor small photovoltaic system is in the right background. Due to the modularity of the Stirling power converters, units can be added as power requirements increase, and units can be replaced at the end of their design lifetimes with new or advanced technology systems. The thrust of power development for the 21st century will aim at lifetime goals of 10, 15, and eventually 30 years, compared to the design baseline of 7 years for present technology development.

CONCEPTUAL LUNAR BASE

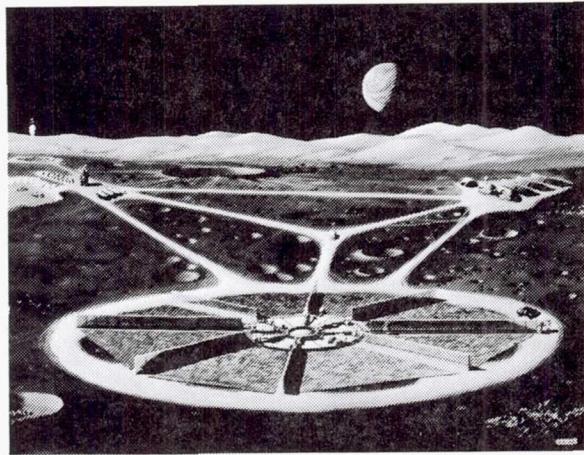


Figure 2

Other possible applications for Stirling Space Power in the multi-hundred kilowatt range include electric propulsion power for science and unmanned cargo missions to the outer planets, power for air and ocean traffic radar control systems, higher power communication platforms and earth observing platforms, and in-space materials processing facilities. Reference [1] provides a description of potential future civil space missions that could be enabled or substantially enhanced by the use of nuclear reactor power.

The requirements and goals foreseen in the 21st century set the framework for the technology programs of the 1990s. The NASA Stirling Space Power Converter Program, shown in Figure 3, is a series of significant steps in technology capability, bringing the free-piston/linear alternator Stirling from its auspicious debut as a technology demonstration in 1985 to its 1050 K space capability in 1996 - the baseline program. Funding for development of the 1300 K machine to utilize the full capability of the SP-100 reactor will be included under the Exploration Technology Program, scheduled for initiation in 1993.

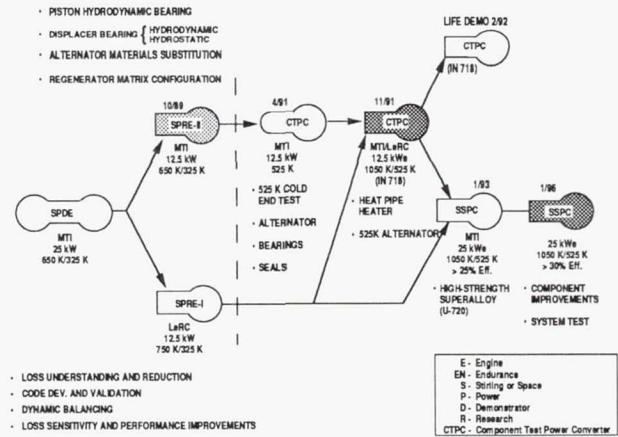


FIGURE 3

STIRLING EXPERIENCE IN SPACE

There is no known experience of Stirling dynamic power conversion systems having ever been flown in space; however, a data base does exist for numerous Stirling cryocoolers which have indeed flown aboard space missions [2]. Stirling cryocoolers operate using the same Stirling cycle as does a power converter, and the basic components are essentially the same. The primary difference between the two devices, stated simply, is that one operates in reverse of the other. A power converter absorbs heat and generates electrical power, usually via a linear alternator which is an integral part of the power piston. A cryocooler operates in reverse - it accepts electrical or mechanical power to drive its power piston; the "hot end" absorbs heat from its "environment" creating localized cryogenic conditions.

Cryocoolers for space applications must meet some very stringent requirements. These requirements include cooling power at the appropriate low temperature with low input power, long lifetime, reliable and maintenance-free operation with minimum vibration and noise, compactness and light weight. Space cryocooler development activity over the last 6 years has been directed at the achievement of 5-year lifetime with a 0.95 mission success rate. References [2] and [3] outline those missions, all of which used kinematic Stirling Cryocoolers. Seven missions were identified; some were missions of only 6 days, others for 2 years. One mission functioned for six years until the satellite was intentionally destroyed. While some of the cryocoolers demonstrated life potential by operating for extended periods of time, they all experienced some type of degradation.

Limited lifetime and degradation of the kinematic coolers is generally attributable to loss of working fluid through elastomeric seals, wear induced degradation due to mechanical rings and seals, and contamination from material outgassing and condensing on the cold finger. Current plans for long-life cryocooler missions call for totally hermetically sealed coolers or use of gold wire seals with concomitant elimination of elastomeric seals; incorporation of non-wearing and non-touching parts via the use of clearance seals and gas bearings, magnetic bearings, or flexure bearings; and improved selection of materials (all metal construction wherever possible) and processes to minimize

outgassing. These evolutionary changes lead to the same goals set forth in the Stirling Space Power Conversion Program.

Reference [2] identifies 6 planned missions from May of 1991 through 1998 which will use the new 5 year life Stirling cryocoolers. All of the long life units in Reference [2] are of the free-piston class of Stirling cryocooler and five use the flexure bearing demonstrated by the Oxford University in the early 1980's. Flexures are used on both the compressor piston and on the displacer; linear motors drive the compressor, and in some cases control the displacer motion.

The fact that Stirling technology in the form of cryocoolers has successfully flown in space, implies that Stirling technology in the form of power converters should likewise perform as planned in the space environment.

THE SPRE POWER CONVERTER

In October of 1986, the 650 K Space Power Demonstrator Engine (SPDE) developed 25 kWe of engine P-V power. Results of this engine testing are discussed in [4] through [6]. The SPDE was a dual-opposed configuration consisting of two 12.5 kWe converters. After this successful demonstration, the engine was cut in half. One half is undergoing testing at NASA-LeRC and the other half has completed testing at the contractor's site, Mechanical Technology Inc. (MTI) in Latham, New York. These power converters are now called Space Power Research Engines (SPRE) and serve as test beds for evaluating key technology areas and components. In [7], it was reported that electrical power of 11.2 kWe at overall efficiency (electrical power out/heat in) of about 19% had been achieved. This is approaching the SPRE design goals of 12.5 kWe and efficiency greater than 20%. The SPRE engine and some of the baseline engine testing are described in some detail in [4] through [13]. Much of the work in the past year has been focused on producing experimental data for validating the HFAST engine performance code, being developed by MTI, as part of a NASA contract. Two areas of study have been: 1.) the sensitivity of the engine performance to the displacer seal clearance, and 2.) the effects of varying the piston centering port area. Cairelli and Swec [14] report that as displacer seal clearance was increased from 2 mil (.002 inch) radial clearance to 5 mils radial clearance, power is only mildly degraded - about 500 watts, and there is no apparent change in measured P-V efficiency. This data implies that the design clearance and tolerances for the displacer could be increased; thus reducing fabrication costs and relieving some of the concern about maintaining close running clearances for long operating periods. They also report that modest increases in both P-V power and efficiency may be achieved by reducing the number of centering ports; but at a sacrifice of bearing port stiffness which could impact the dynamic response and stability of the system.

Testing in the remainder of 1991 will attempt to verify potential performance improvements suggested by HFAST studies conducted by MTI. Power improvements as great as 3 kWe with accompanying efficiency gains of 2% may be achievable.

THE COMPONENT TEST POWER CONVERTER (CTPC)

The Component Test Power Converter (CTPC) is a logical intermediate step providing an incremental evaluation of critical technologies to be incorporated into the 25 kWe Space Power Converter. Those critical technologies have been identified as: bearings, materials, coatings, linear alternators, mechanical and structural issues, and heat pipes. The CTPC "cold" end provides a test vehicle to identify problem areas and develop individual "cold" end components and sub-assemblies. Specifically the CTPC "cold end" will provide early test and evaluation of the mechanical design at 525 K, bearing operation at 525 K, and structural and mechanical design of the linear alternator.

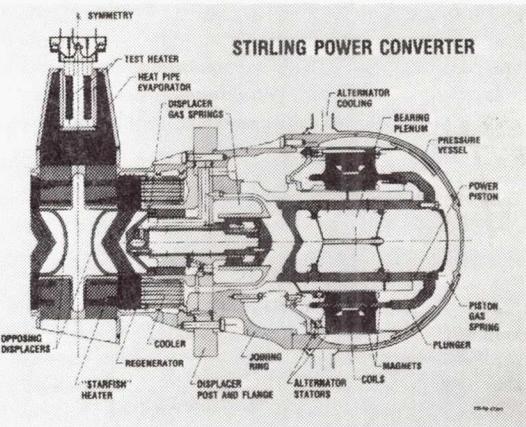


FIGURE 4

CTPC Cold End Testing

The hot end of the CTPC will not be available until the Fall of 1991. It was considered prudent to take advantage of this interim time period to evaluate the impact of temperature on close clearance seal and bearing surfaces in the cold end of the power converter; the potential for binding of close clearance reciprocating surfaces increases with increase in operating temperature. The linear alternator is being powered by an external power supply and functions as a linear motor to drive the power piston in a reciprocating manner, thus simulating the operation of the power converter. A hot oil is pumped through the "cooler" heat exchanger creating a temperature environment similar to that expected in the functioning power converter. The design approach for the CTPC running surfaces was to use an abradable surface, carbon graphite sleeve, against a hard surface, aluminum oxide. The abradable surface must be soft enough to wear rather than cause a jam in the event of a rub. Following testing at each temperature increase, the converter is disassembled and inspected, looking for evidence of rubs. Testing began at room temperature conditions and has been gradually increased to 420 K without incident. Testing will continue, by incrementally increasing temperature, until proper operation has been achieved at the final cold end temperature of 525 K.

CTPC Linear Alternator

The prior generation SPRE linear alternator demonstrated greater than 90% efficiency in an operating power converter at design conditions: 150 bar pressure, a temperature ratio of 2, and 10 mm piston amplitude. This alternator demonstrated a basic understanding of linear machine technology and validated the design codes used in its development.

The current generation CTPC linear alternator is quite similar in design to the SPRE with the exception that it must operate at a cold end temperature of nominally 525 K, 200 K hotter than the SPRE. Because the alternator could reach a peak temperature of 575 K, close to the upper operating limits of Samarium₂ Cobalt₁₇ magnets, a test facility was developed at LeRC to characterize samples of magnets from a variety of vendors at power converter operating temperatures. Results indicate that sufficient design margin exists for Sm-Co magnets operating at this temperature, if the design takes into account the effects of high temperatures on magnet performance. [15]

Early testing of the CTPC alternator has yielded an 85% efficiency. A bench top investigation has shown that the alternator was damaged during fabrication - many of the individual magnet segments are electrically shorted to their supporting Inco 718 tie rods and spacer rings; the shorts permit eddy current losses. As designed, each magnet was to be electrically insulated from its support structure. Because the alternator generates greater than desired losses, these additional losses will be manifested as heat and will actually provide a worst case test condition for this phase of high temperature testing. A second alternator is being fabricated using a deep oxide technique on the magnets to guarantee good electrical insulation and to demonstrate the expected efficiency. This technique should be acceptable for the final space design because the approach eliminates organic insulating materials which can outgas and contaminate the Helium working fluid.

1300 K REFRactory STIRLING POWER CONVERTER

The current Stirling technology development contract with MTI specifies a superalloy power converter which must be capable of operating for 60,000 hours at a hot end temperature of 1050 K and a cold end temperature of 525 K (temperature ratio of 2). 1050 K is the highest temperature deemed feasible for superalloy use. While this is an intermediate step to demonstrate technology solutions to problems associated with the effects of high temperature gas bearings, clearance seals and other close fit components, the 1050 K power converter could actually be considered for space power applications with the SP-100 reactor operating at 1100 K; this technology could also be applied to solar dynamic power conversion. Certainly one advantage of superalloy technology is its compatibility, without special surface treatment, with the carbon dioxide atmosphere of Mars. The ultimate goal, however, of the space Stirling program is to develop the technologies for a refractory metal Stirling power converter with a hot end temperature of 1300 K and a cold end temperature of 650 K; 1300 K is considered the maximum outlet temperature from the SP-100 reactor and gives the concomitant system advantages shown in Figure 1. The objective is to take 1050 K superalloy technology and to evolve into 1300 K technology by direct substitution of refractory materials. The Materials Division at NASA LeRC has substantial experience in the application of refractory materials, and has been developing materials for use in the hot components of the SP-100 reactor. As a first step toward the 1300 K technology development for the Stirling power converter, the Materials Division has compiled a list of refractory material candidates (Table 1). The table lists the LeRC ratings for each alloy as to joinability, fabricability, availability, data, and vacuum required, on a scale of 0 to 10 with 10 being the best. The current contract with MTI calls for the refractory design to be carried through the conceptual design phase. That activity has started and will continue through FY91.

TABLE 1
REFRACTORY MATERIAL CANDIDATES FOR 1300K STIRLING

BASE MATERIAL	MP (K)	ρ (g cc)	ALLOY NAME	COMPOSITION (wt%)	JOINABILITY	FABRICABILITY	ALLOY AVAILABILITY	DATA AVAILABILITY	VACUUM (torr)
W	3680	19.3	W-25Re-HfC	24-26% Re 1% HfC	5	4	4	3	10^{-6}
Ta	3270	16.6	ASTAR-811C	8% W 1% Re 1% HfC	8	8	10	5	10^{-8}
Mo	2880	10.2	TZM	0.08% Zr 0.5% Ti	2	8	10	4	10^{-6}
			TZC	1.25% Ti 0.1% Zr 0.15% C	2	6	10	4	10^{-6}
Mo-Re	2780	15.5	Mo-47.5 Re	47.5% Re bal Mo	8	6	8	3	10^{-6}
Nb	2740	8.6	FS-85	11% W 28% Ta 1% Zr	8	8	5	4	10^{-8}
			B-88	27% W 2% HfC	7	7	4	2	10^{-8}
			C-103	10% Hf 1% Ti 0.7% Zr	10	10	10	7	10^{-8}
			PWC-11	1% Zr 0.1% C	10	10	10	7	10^{-8}
			Nb-1Zr	1% Zr	10	10	10	8	10^{-8}

STIRLING LIFE AND RELIABILITY

Reference [2] provides a data base which shows the operating experience of numerous models of Stirling machines: kinematic and free-piston, high-power and low-power, cryocoolers and power generators. Some Stirling machines (typically free-piston machines) have achieved long life by incorporating non-contact bearings, while other Stirling machines (typically kinematic machines) have achieved long operating life through regular seal and bearing replacements.

Several examples of long-lived Stirling machines are reported; one outstanding example is the 10.7 watt, radioisotope heated Harwell D-2 Lab Unit reported by E.H. Cooke-Yarborough in 1990. This diaphragm type Stirling was taken out of service on May 22, 1987 with 110,000 hours of continuous service and 3.3×10^{10} oscillations. [16]

The "Stirling Experience In Space" section of this paper shows that 5 year life for free-piston Stirling cryocoolers is an attainable goal. Reference [2] cites three examples of kinematic Stirling cryocoolers used on space missions which demonstrated life from 2 to 5 years, and this was accomplished using engineering prototypes not even designed with the space application in mind. In 1983, under NASA contract DEN 3-333, Mechanical Technology Incorporated (MTI) began endurance testing of the EM-2 free-piston Stirling engine. The EM-2 was a nominal 2 kWe machine incorporating a combustion heater, hydrostatic gas journal bearings, and saturated plunger type linear alternator. The power converter was operated at low-power conditions and full-power conditions over 262 planned starts/stops. At the end of 5385 hours, only minor scratches were discovered due to the numerous dry starts/stops and no debris was generated [17, 18]. The heater temperature for this power converter was 1033 K - similar to the heater temperature for the superalloy space power converter (1050 K).

The heater head of Stirling power conversion systems is the major design challenge in that heater head creep is predicted to be the life-limiting mechanism for Stirling. The difficulty in creep analysis stems from inadequate knowledge of elevated temperature material behavior and inadequate knowledge of inelastic analysis techniques. Typically, the high operating temperatures and long operating periods of Stirling engines are taxing the ultimate capabilities of even the strongest superalloys. A Stirling engine designer should be aware of such high temperature phenomena as ductility troughs, dynamic strain aging, creep thresholds, creep ratchetting, creep-fatigue interaction, thermomechanical fatigue, etc..., for these will limit the heater head's long term durability. The designer should also be aware that the typical elastic-plastic finite element (FEM) analysis is inappropriate for the heater head at these extreme temperatures. An elastic-plastic FEM analysis for the heater head has the problem of being a time independent analysis while the dominating material behavior for this application is time dependent. Thus, an inelastic FEM analysis incorporating an appropriate viscoplastic constitutive model should be utilized in the heater head analysis and design. [19]

The proposed Starfish heater head design of the Space Stirling Power Converter simplifies the manufacture and extends the life capability of the Stirling Hot End (Fig. 5). In the Starfish design there are a multitude of passages in each fin. The outer most passage location of each fin is an area of concern. In order to minimize the temperature drop in the system, the wall thickness of this passage is very thin (≈ 0.75 mm) and the stress state is

biaxial due to the internal pressure stresses and axial stress. The magnitude of this biaxial stress state will increase with time due to creep (or relaxation) mechanisms. The goal of this program element is to study the heater head problems both experimentally and analytically, and then incorporate these findings into the final design. This will also include a life assessment of the final heater head design.

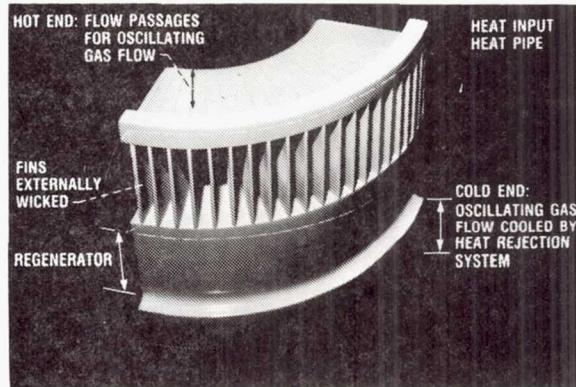


FIGURE 5 - STARFISH HEATER HEAD

Analyses have already shown that start-stop cycles and the phenomena of thermomechanical ratchetting must be considered when designing Stirling heater heads. [20] Figure 6 shows that for space nuclear applications, where starts-stops are limited, the heater head can run at significantly hotter temperature than those terrestrial applications requiring orders-of-magnitude higher starts-stops.

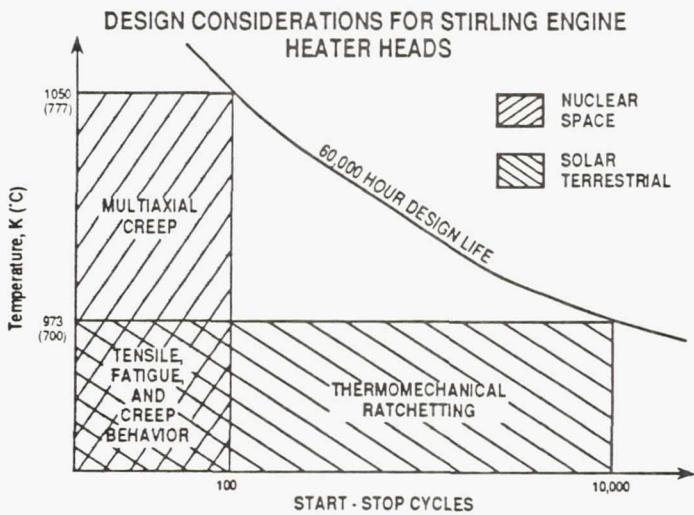


FIGURE 6

CONCLUDING REMARKS

- o Stirling Space Power Converters have the potential to significantly advance the state-of-the-art of nuclear space power systems, and can provide low mass, compact power systems for a wide range of NASA future missions.
- o Stirling machines in the form of kinematic cryocoolers, have already flown successfully on long-term space missions.
- o Development testing and improvement of the Space Power Demonstrator Engine will demonstrate the flexibility and ultimate performance capability of the original free-piston/linear alternator 25 kWe machine. The design codes will be modified and verified by the test results to enhance future designs.
- o Component test development will be carried out at the 12.5 kWe per cylinder size, to demonstrate the viability of new designs for a 1050 K hot end, 525 K cold end, 50 kWe Space Stirling Power Converter.
- o Initial design processes leading toward a 1300 K hot-end Stirling machine at 50 kWe, have begun to identify materials applicability for construction of the next generation of Stirling Space Power Converters.
- o Analytical predictions of the life limiting mechanisms for Stirling Power Converters will be correlated with experimental data and integrated with the design process to produce a realistic assessment of the final machine lifetime.

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